PATHWAYS TO REDUCTION OF CO_2 EMISSIONS FROM COMBUSTION ENGINES

Alok Warey, Ph.D.

OUTLINE

- Part 1: Technology Screening to meet 2025 CO_2 Emissions Regulations (Co-PI) – On-going
- Part 2: Fundamental Exhaust Gas Recirculation (EGR) Cooler Fouling and Mitigation Study (PI) - Completed
- Quick overview of other projects

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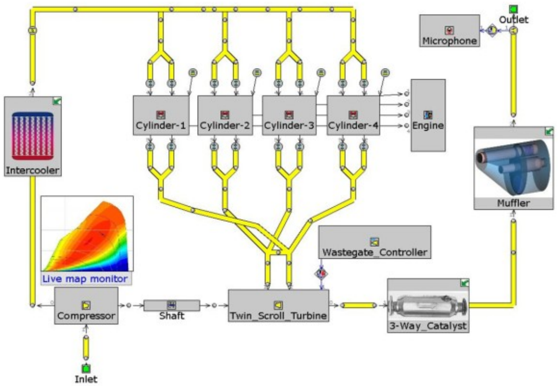
OBJECTIVE

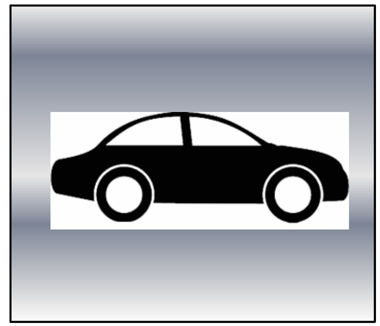
- *Explore diesel engine technology combinations that meet 2025 CO_2 regulations consistent with future emissions standards*
- *Remain cost competitive*

METHODOLOGY



1-D Engine Model

+



Vehicle Model

CO_2 (g/km)

- CO_2 emissions estimated for different diesel engine technologies over the New European Driving Cycle (NEDC) and the Worldwide Harmonized Light Vehicles Test Procedure (WLTP)

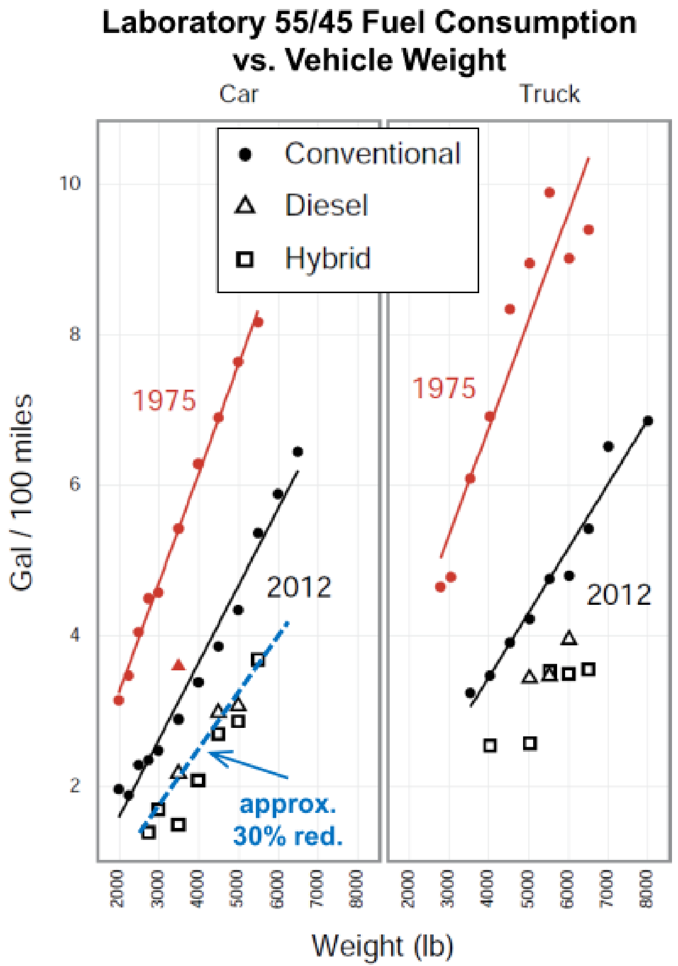
DIESEL ADVANTAGE OVER GASOLINE

- Data from EPA show approximately 30% reduction in gallons/100 miles for diesel (approx. 40% higher MPG)

- Why is a diesel engine more efficient that a conventional gasoline engine?

  Common answers:
  - No throttling losses
  - Higher compression ratio

- These are contributors, but the lean combustion process of the diesel engine is the main factor leading to efficiency gain



Source: Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2012, EPA, 2013

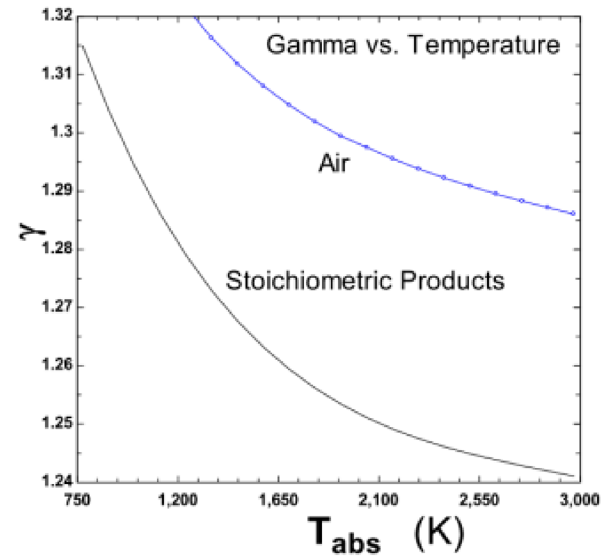
LEAN COMBUSTION

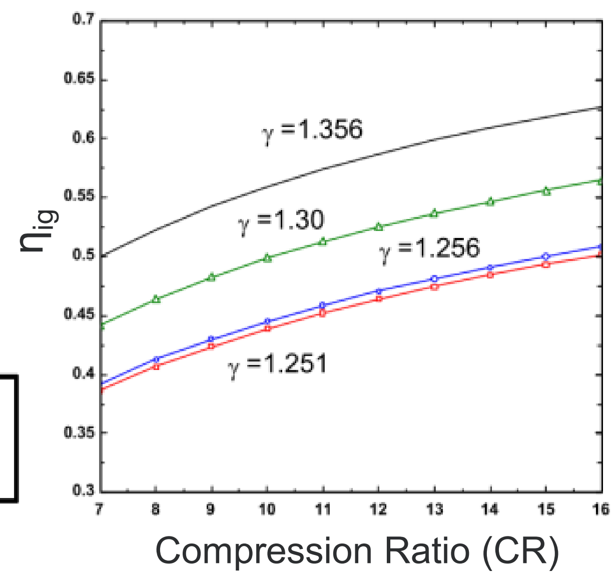
- Increased dilution improves indicated fuel conversion efficiency by lowering temperatures and increasing gamma (ratio of specific heats).

- Switching from exhaust dilution to air dilution improves indicated fuel conversion efficiency by increasing gamma.

- Increased dilution improves the indicated efficiency by lowering temperatures and decreasing heat losses.

$$\boxed{\eta_{ig} = 1 - \frac{1}{CR^{(\gamma-1)}}}$$



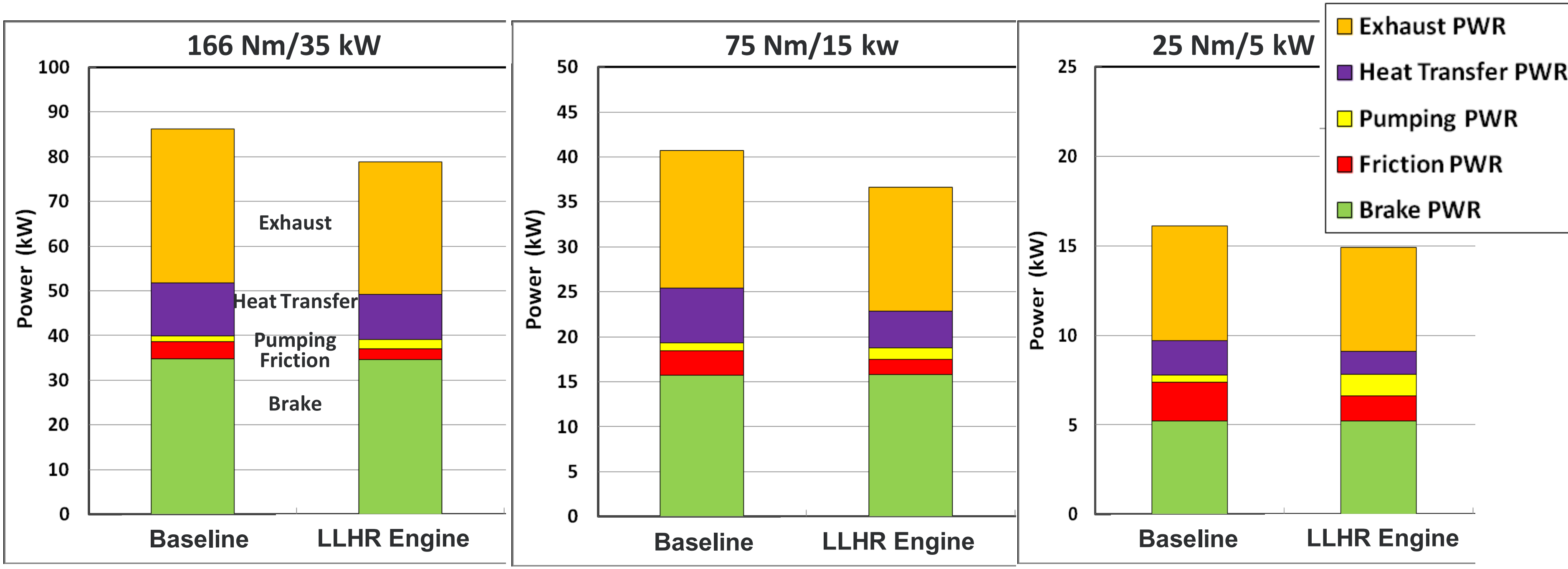


Source: Foster, Combustion Engines Efficiency Colloquium, DOE 2010

LOW HEAT REJECTION

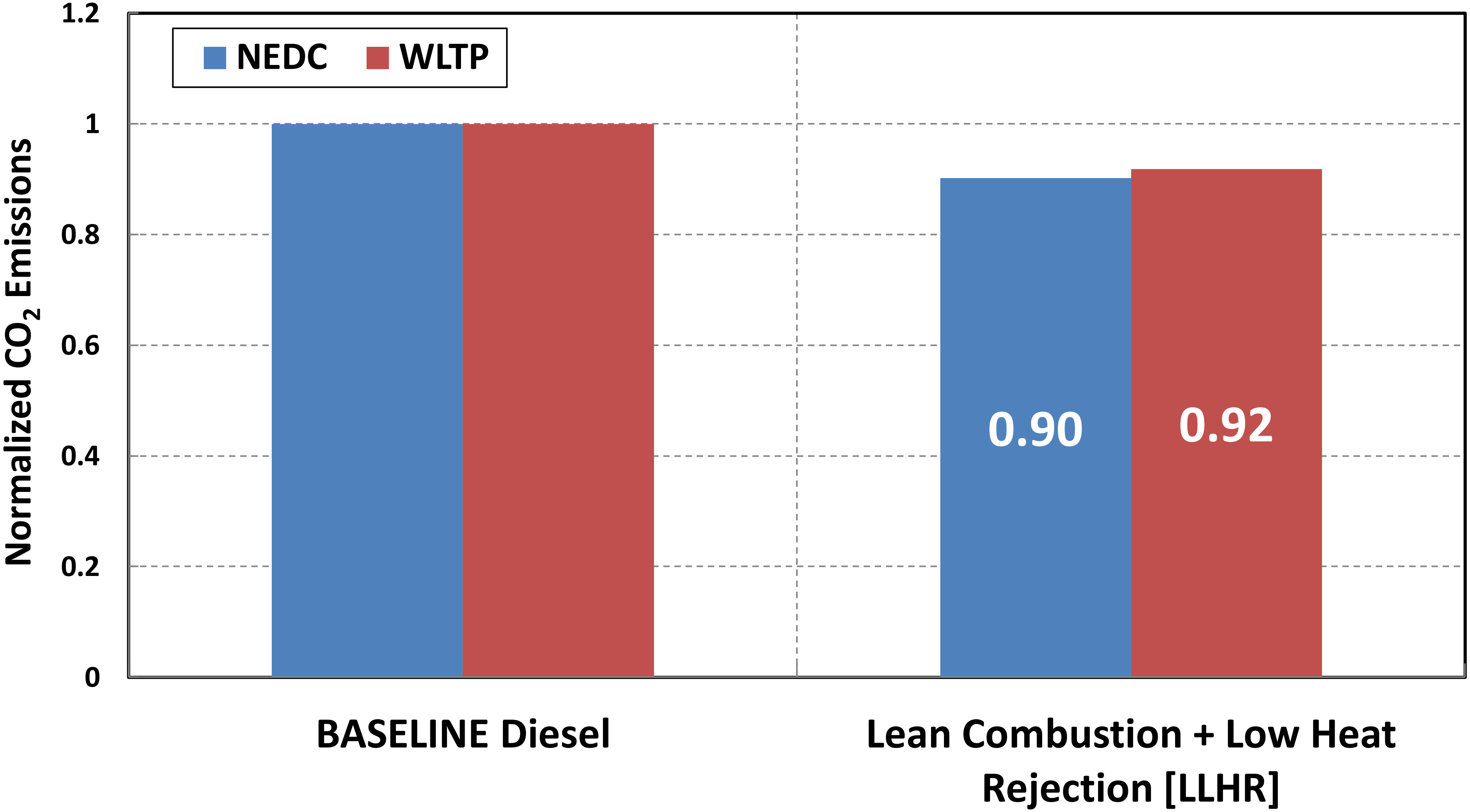
- In-cylinder heat losses in modern diesel engines constitute a significant part of thermodynamics losses.
- Engine efficiency can be increased by retaining a greater amount of combustion energy for conversion to mechanical work.
- Sensitivity studies show that, provided heat losses could be minimized, there is potential for significant fuel consumption improvement.
- Several pathways to achieve low heat rejection.

BASELINE DIESEL *vs* LEAN LOW HEAT REJECTION (LLHR) ENGINE
FUEL ENERGY BREAKDOWN



- Combined pumping and friction torques are comparable
  - Boosting system for lean combustion adds more pumping torque
- Due to leaner combustion and higher *effective* expansion ratio the LLHR engine is more efficient
  - Centroid of heat release closer to TDC for similar peak cylinder pressure and cylinder temperatures
- Lower energy in the exhaust

CO_2 EMISSIONS



SUMMARY

- Developing robust, cost-effective, lean combustion and low heat rejection diesel engines will be challenging but the fuel economy benefits are significant.

- Challenges for engine optimization:
  - Robust combustion control over all operating conditions
  - Robust emissions control over all operating conditions
  - Good fuel consumption under real world driving conditions
  - Low combustion noise
  - Exhaust temperature

- This will require a coordinated effort between air handling, combustion, aftertreatment and controls – a system optimization approach.

- In order for this to work effectively it is important to focus research on fundamental insights that have long-term value critical to achieving upper-bound efficiency and lower-bound emissions.

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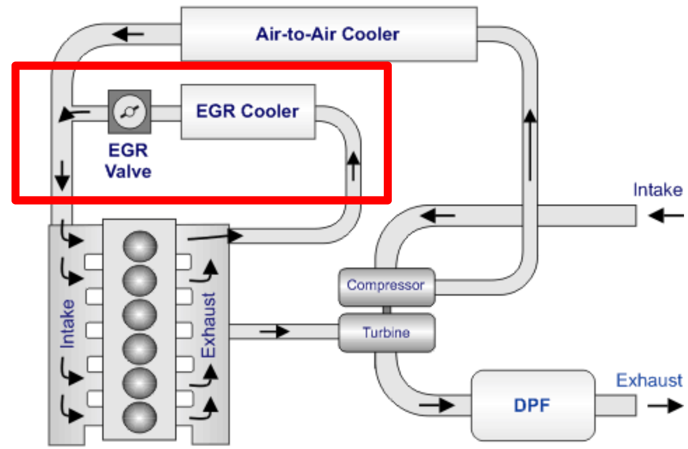
EXHAUST GAS RECIRCULATION (EGR) COOLERS

- EGR coolers are compact heat exchangers used on all modern diesel engines to cool exhaust gasses that are re-circulated into the combustion chamber.

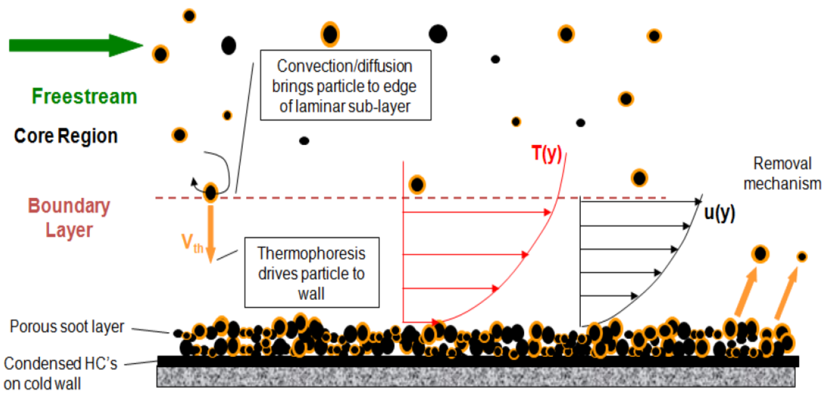
- Exhaust gas recirculation is used to control NOx (oxides of nitrogen) emissions that result from diesel combustion.

- Advanced diesel combustion strategies to improve fuel economy rely on cooled exhaust gas recirculation (EGR).



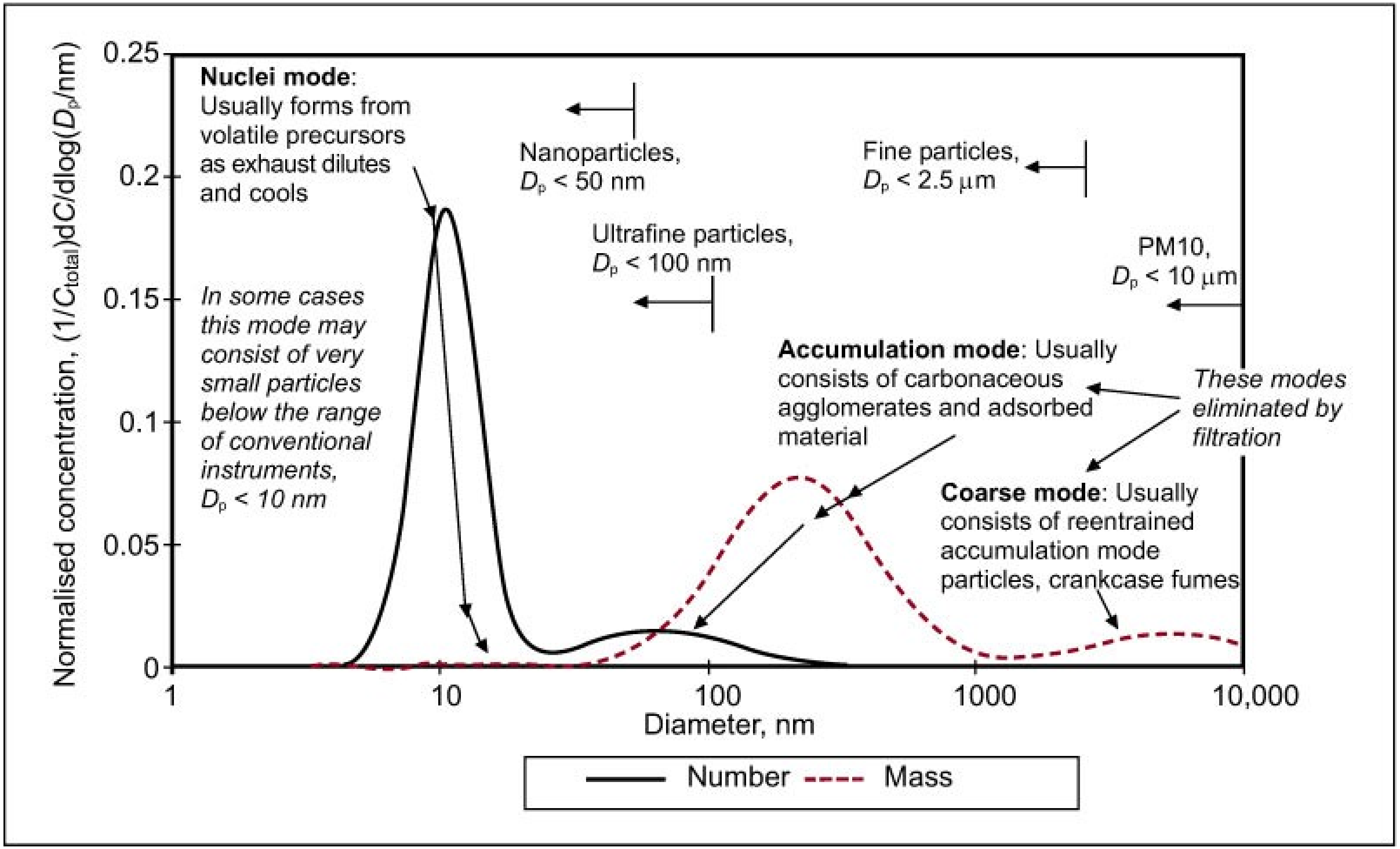
EGR COOLER FOULING

- Fouling of exhaust gas re-circulation (EGR) coolers can result in significant deterioration of the cooler effectiveness and increased pressure drop across the cooler.
- EGR cooler fouling can adversely affect the combustion process, engine durability and emissions.
- Complicated flow physics with multiple soot particle deposition and removal mechanisms. Hydrocarbon and water condensation in addition to soot deposition.
- Goal of this research was to develop a fundamental understanding of EGR cooler fouling mechanisms and demonstrate novel concepts to mitigate fouling and regenerate fouled EGR coolers.



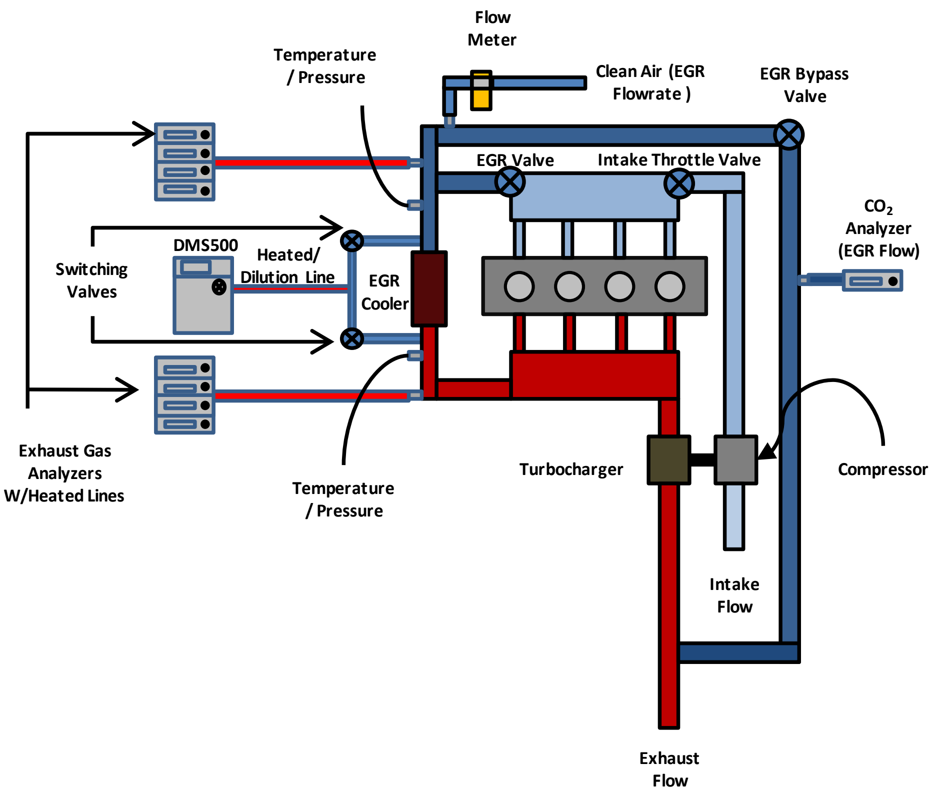
Source: SAE 2010-01-1211

DIESEL EXHAUST PARTICLE EMISSIONS

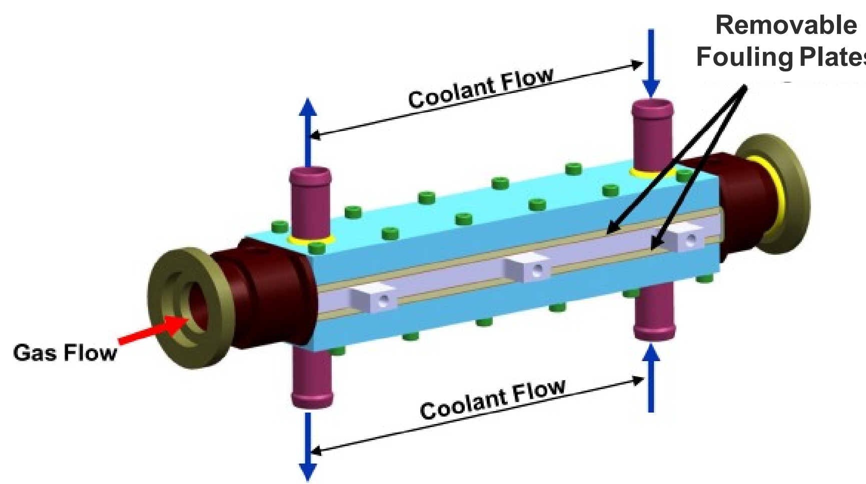


Source: David Kittelson, University of Minnesota

EXPERIMENTAL SETUP

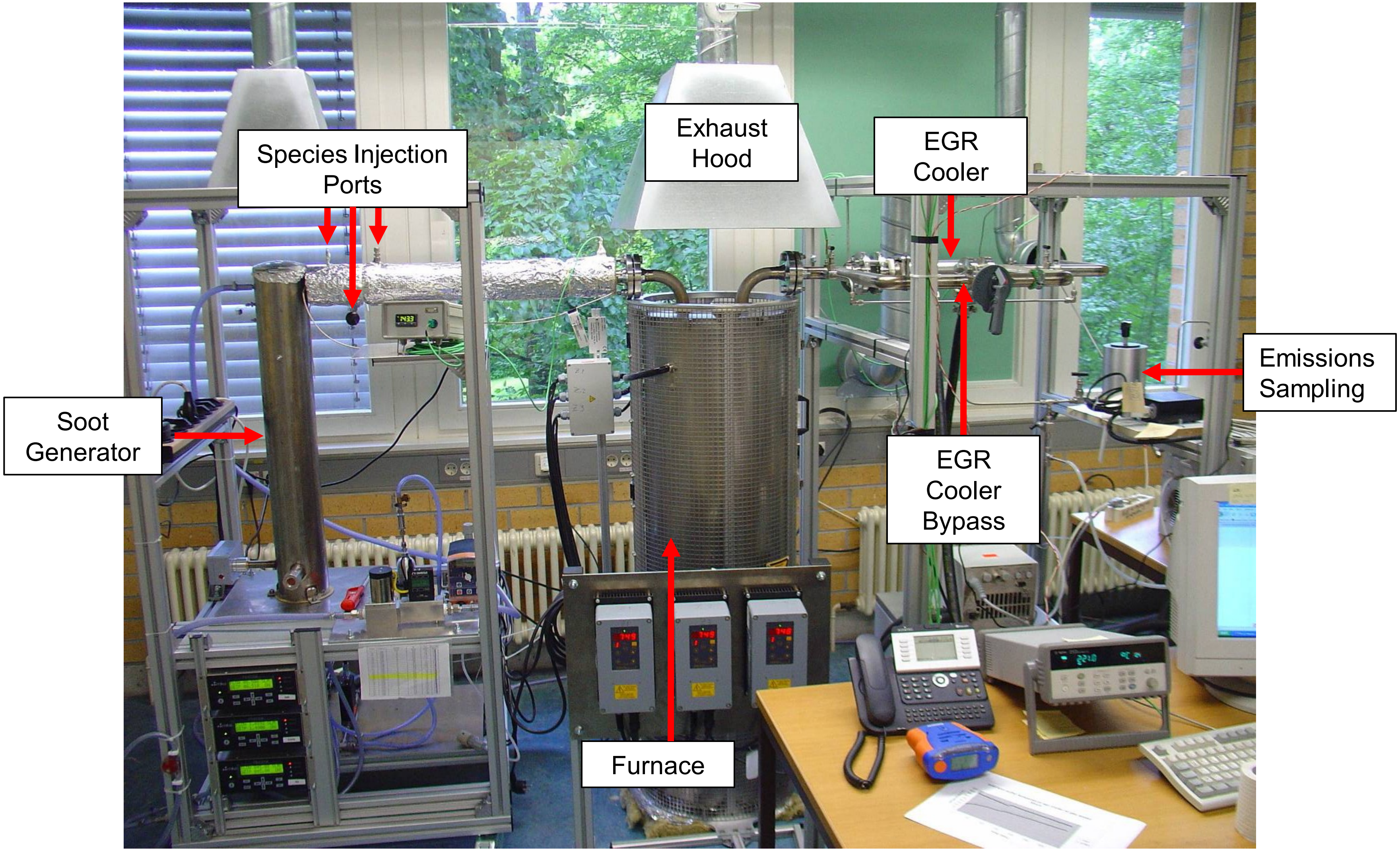


Engine Test Stand at GM R&D



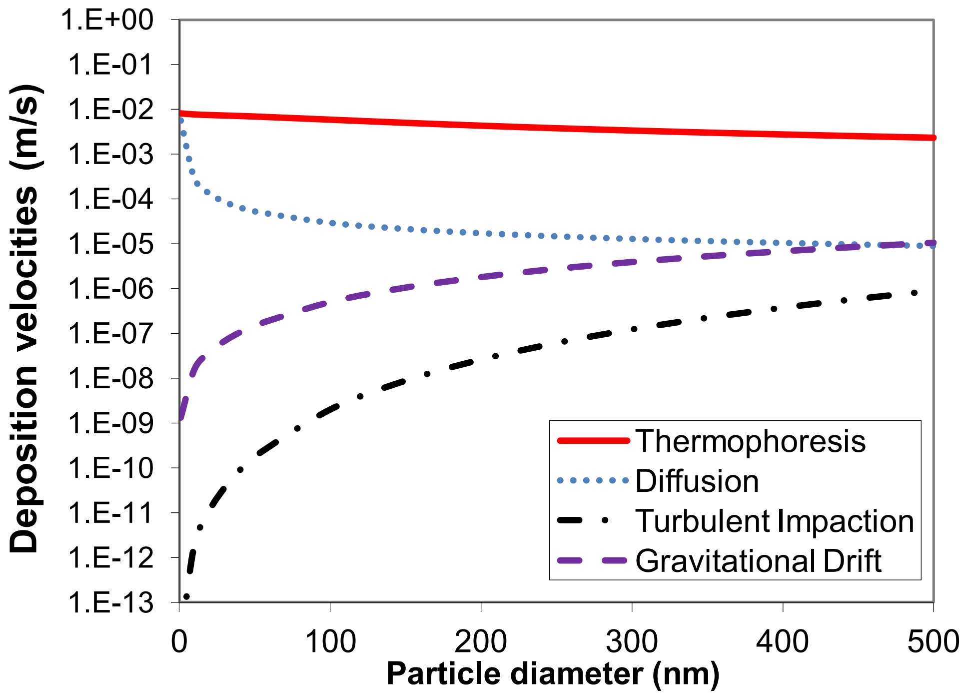
Single Rectangular Channel EGR Cooler

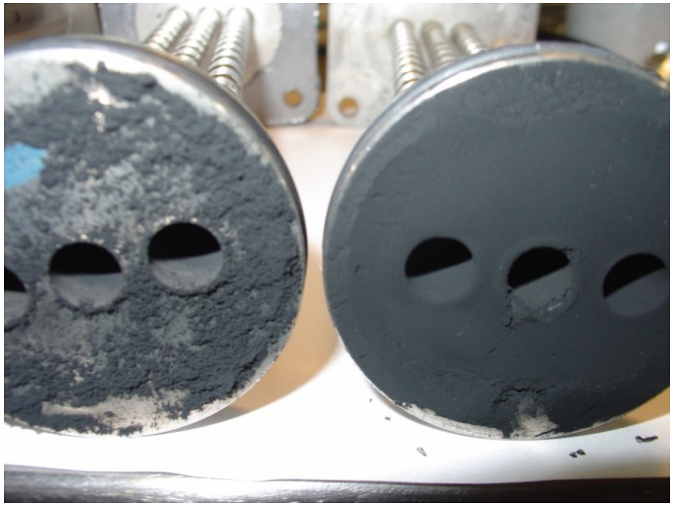
EXPERIMENTAL SETUP



Lab Reactor – University of Stuttgart

THERMOPHORESIS





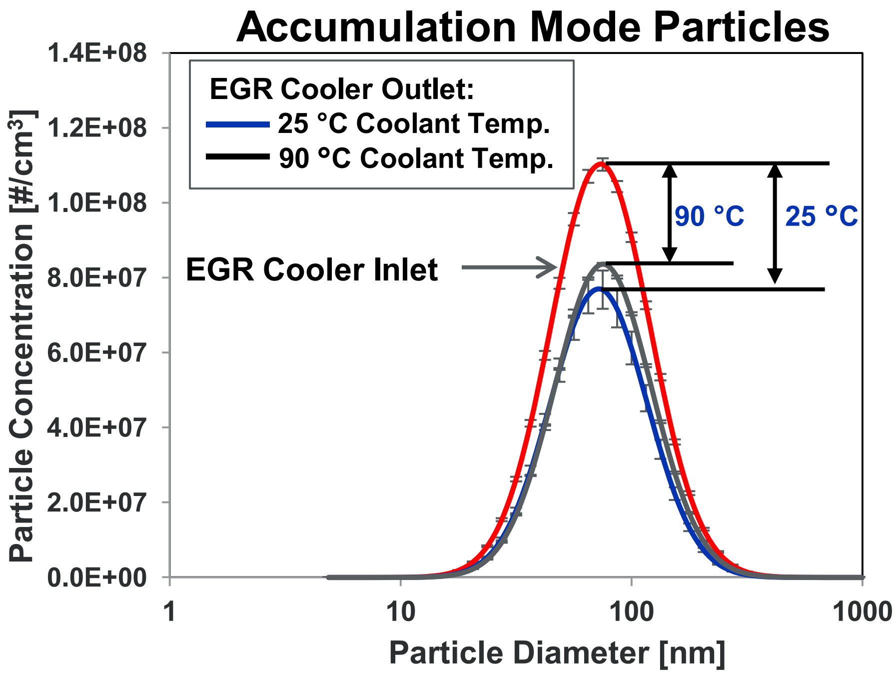
Left: ΔT ~ 0 °C (Isothermal)　　**Right: ΔT ~ 300°C (Thermophoresis)**

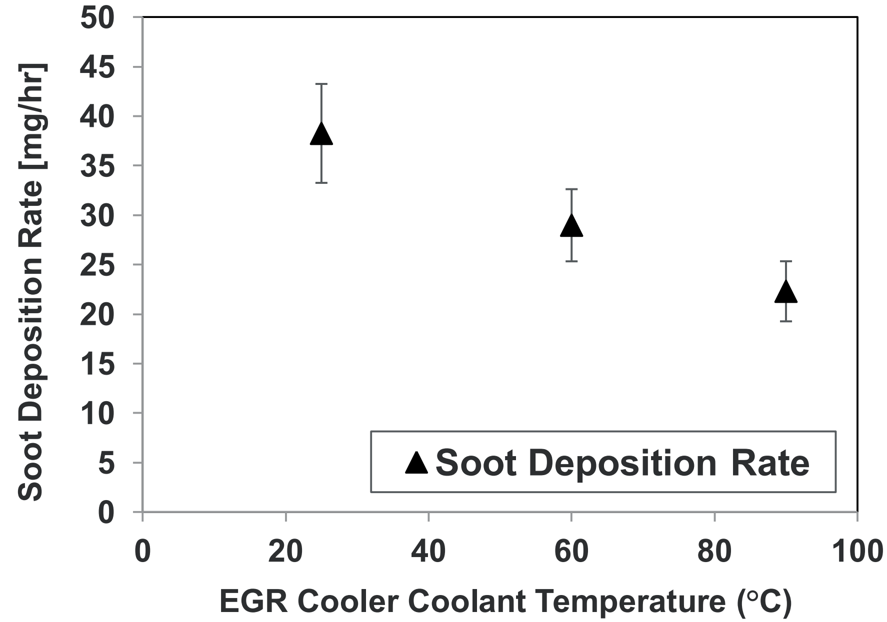
- Thermophoresis* is the dominant mechanism for particle deposition in EGR coolers.

- Fouling will always occur as a result of the temperature difference, which is necessary for heat exchanger operation.

* Thermophoresis = Particle transport due to temperature difference (ΔT)

THERMOPHORESIS

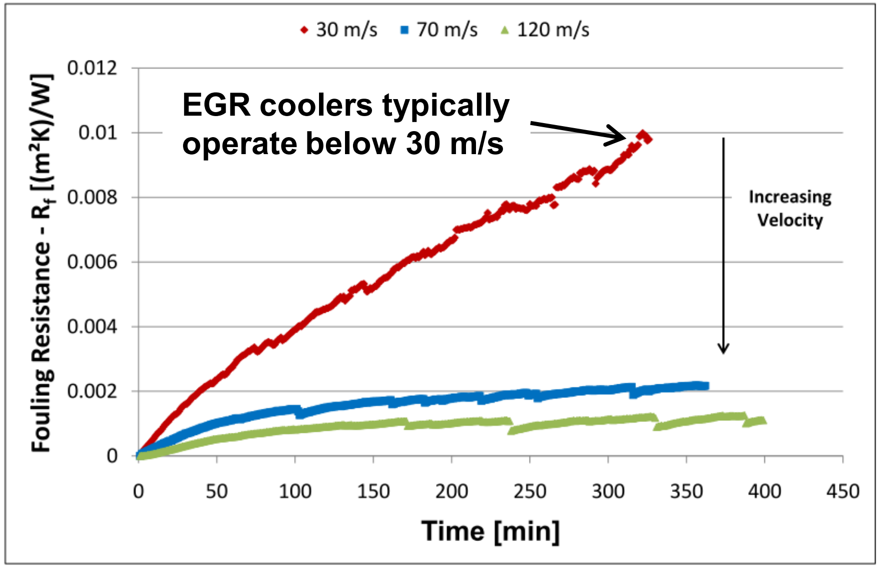


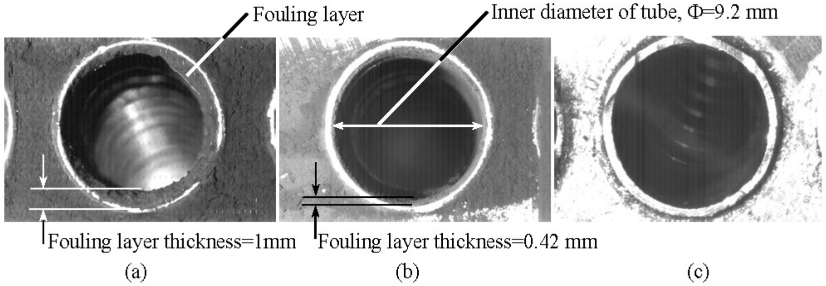


- Particle measurements upstream and downstream of the EGR cooler also show evidence of thermophoresis.
- Soot deposition rate due to thermophoresis increases with decrease in coolant temperature.

Bika, A.S., **Warey, A.**, Long, D., Balestrino, S., and Szymkowicz, P.G., "Characterization of Soot Deposition and Particle Nucleation in Exhaust Gas Recirculation Coolers", ***Aerosol Science and Technology***, 46(12): 1328-1336, 2012.

PARTICLE REMOVAL



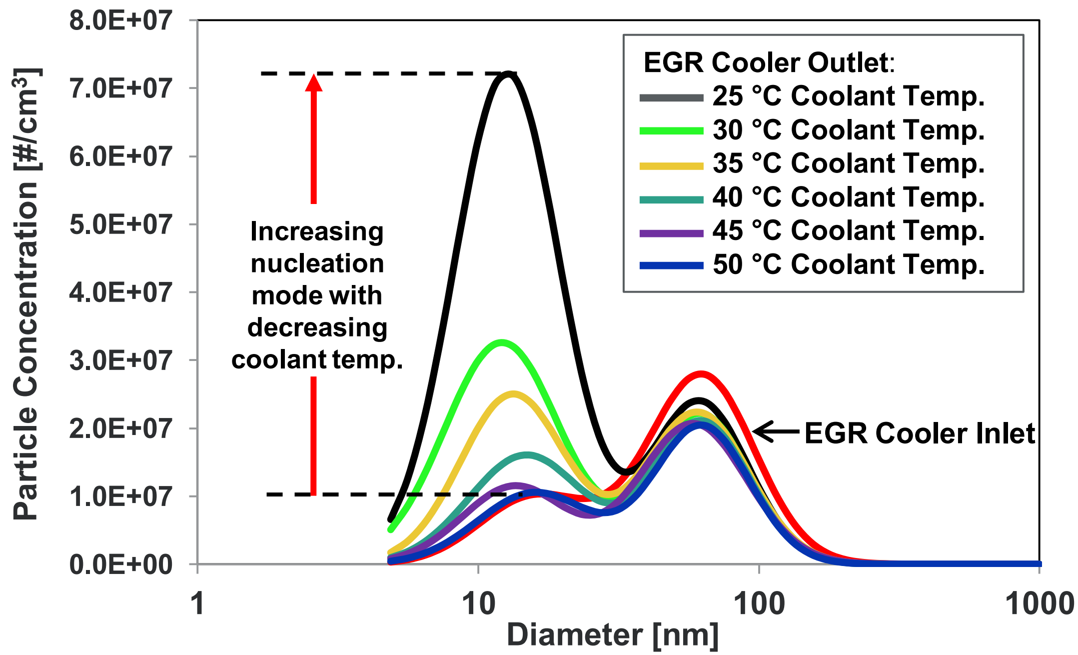


30 m/s **70 m/s** **120 m/s**

- Increasing wall shear stress due to gas velocity appears to be effective in preventing dry soot accumulation on the cooler walls.
- However, typical gas velocities through the EGR cooler are considerably lower than 30 m/s for reasons of excessive pressure drop.
- It is impractical to generate the high gas velocities necessary for deposit removal through the cooler of a conventional diesel engine.

Abd-Elhady, M. S., Zornek, T., Malayeri, M. R., Balestrino, S., Szymkowicz, P. G., & Müller-Steinhagen, H., "Influence of Gas Velocity on Particulate Fouling of Exhaust Gas Recirculation Coolers", ***International Journal of Heat and Mass Transfer***, 54(4): 838-846, 2011

PARTICLE FORMATION



- As the coolant temperature is decreased below 45 °C, nucleation mode particle concentration begins to increase downstream of the cooler. This trend is continued as the coolant temperature is decreased further.

- Condensation of hydrocarbons occurs not only on the cooler walls but also in the bulk gas.

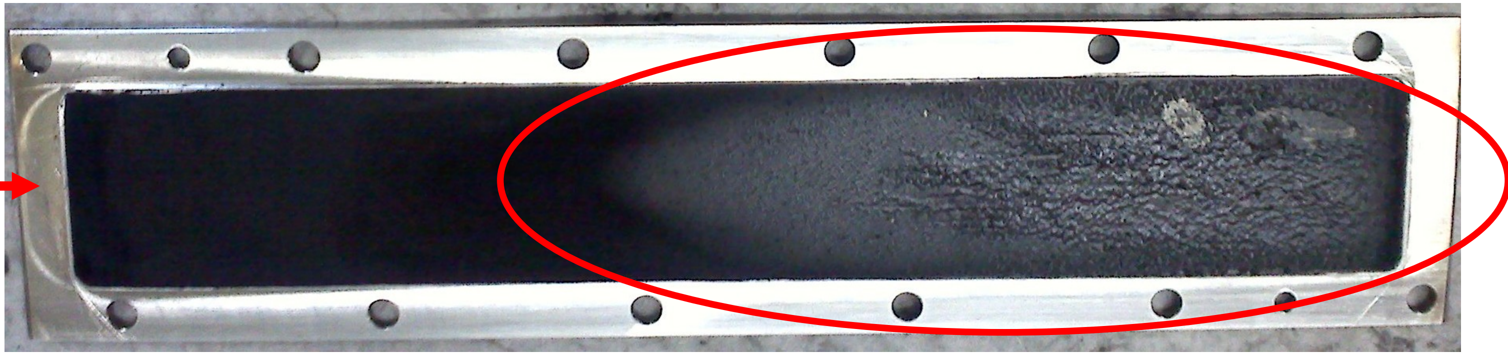
Bika, A.S., **Warey, A.**, Long, D., Balestrino, S., and Szymkowicz, P.G., "Characterization of Soot Deposition and Particle Nucleation in Exhaust Gas Recirculation Coolers", ***Aerosol Science and Technology***, 46(12): 1328-1336, 2012.

Warey, A., Bika, A.S., Long, D., Balestrino, S., and Szymkowicz, P.G., "Visualization and Analysis of Condensation in Exhaust Gas Recirculation Coolers", SAE Paper 2013-01-0540.

EFFECT OF HYDROCARBON (HC) CONDENSATION

Tin = 215 ° C
FSN = 2.0
THC = 40 ppm C3
Flow: 200 SLPM
Exposure : 2 hours
Tcoolant: 25 C

Tin = 215 °C
FSN = 2.0
THC = 250 ppm C3
Flow: 200 SLPM
Exposure : 2 hours
Tcoolant: 25 C



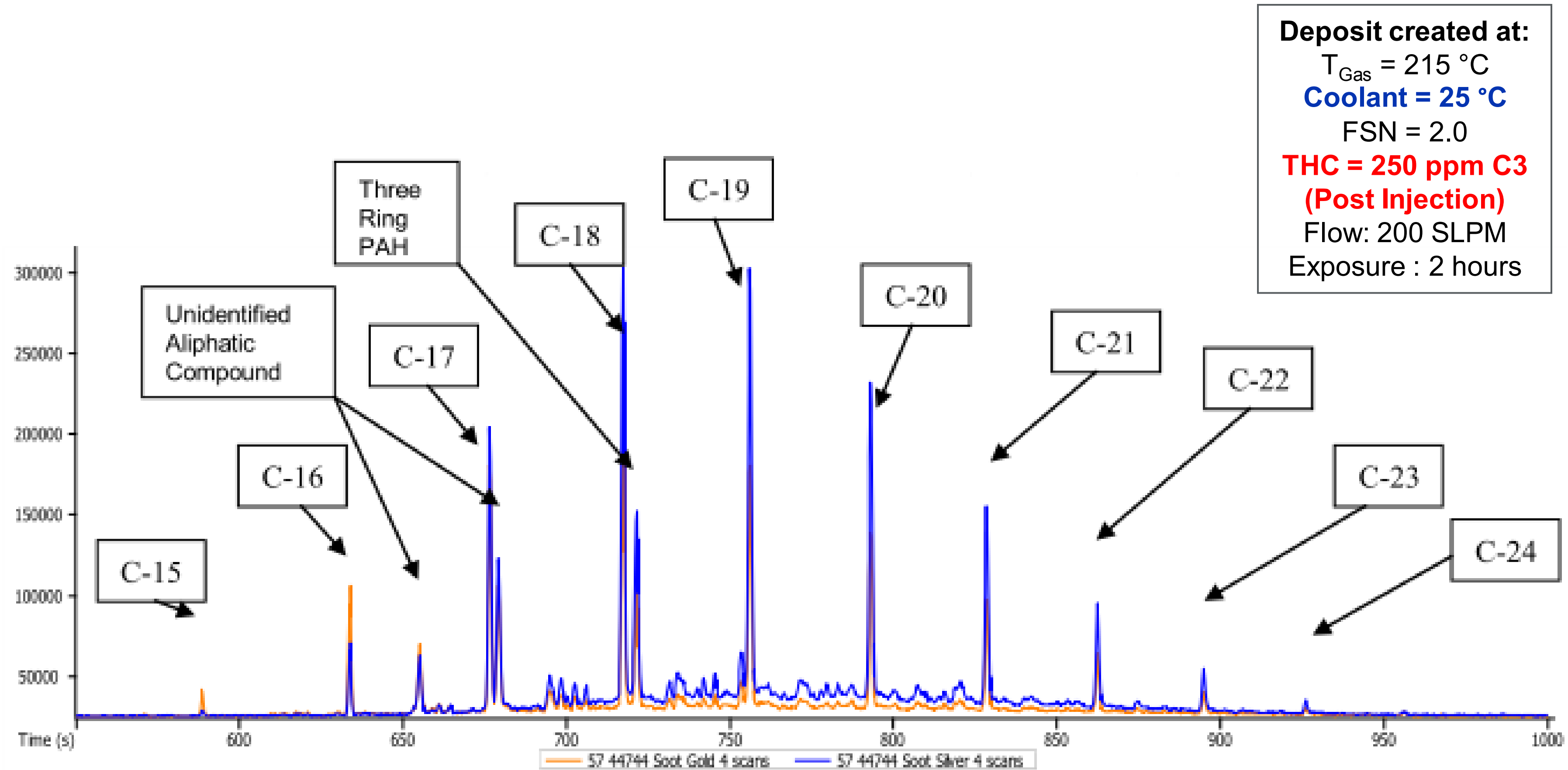
Inlet **Outlet**

- Significant changes in deposit morphology were observed due to hydrocarbon condensation.

- Condensed HC's in the EGR cooler diffuse through the deposit layer and stay near the cold wall. Cold wall inhibits evaporation of condensed HC's.

Bika, A., **Warey, A.,** Long, D., Balestrino, S., & Szymkowicz, P., "An Investigation of Diesel EGR Cooler Fouling And Effectiveness Recovery", SAE 2013-01-0533

DEPOSIT ANALYSIS

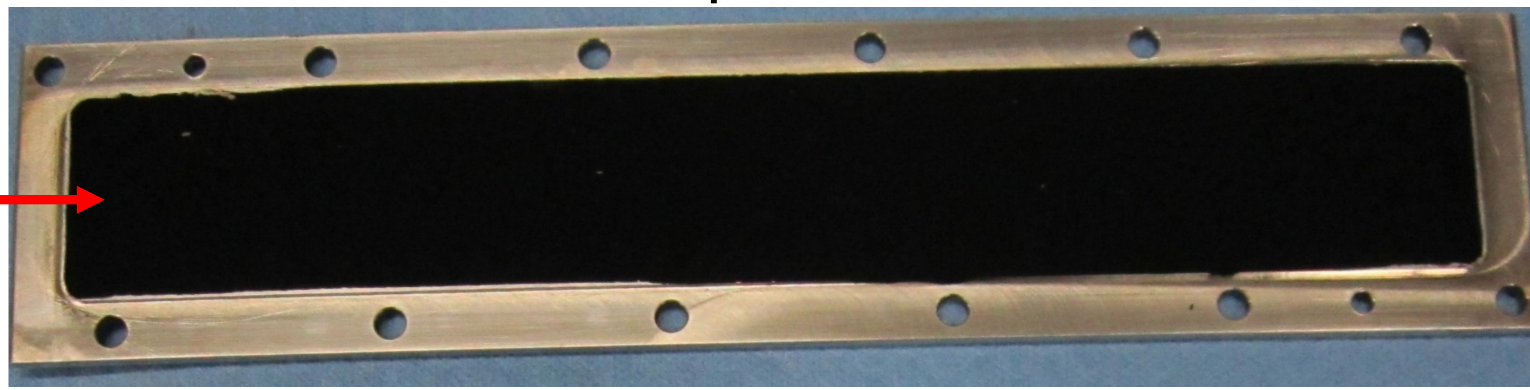


- Heavier hydrocarbons in diesel fuel tend to condense at coolant/wall temperatures typically encountered in EGR coolers.

EFFECT OF WATER VAPOR CONDENSATION

Prior to Water Vapor Condensation

Tin = 215 °C
FSN = 2.0
THC = 40 ppm C3
Flow = 200 SLPM
Exposure = 2 hours
Coolant = 100 °C



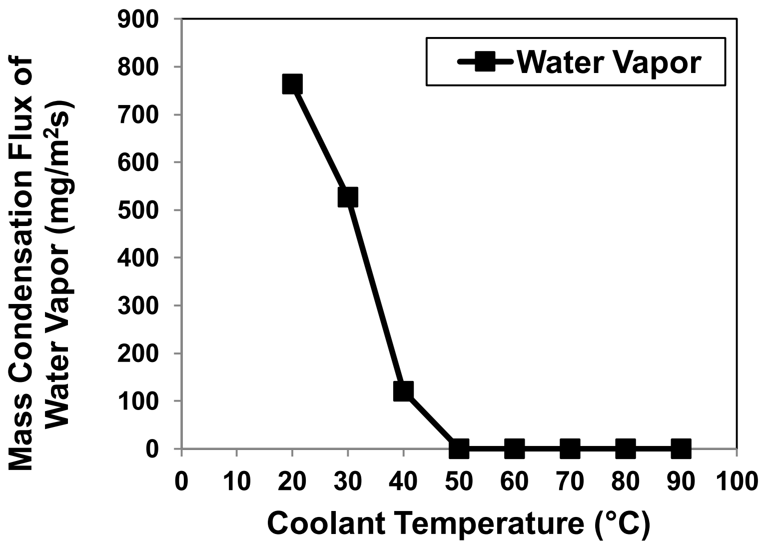
After Exposure to Water Vapor Condensation

Tin = 145 °C
FSN = 0.3
THC = 65 ppm C3
Flow = 200 SLPM
Exposure = 30 min
Coolant = 10 °C

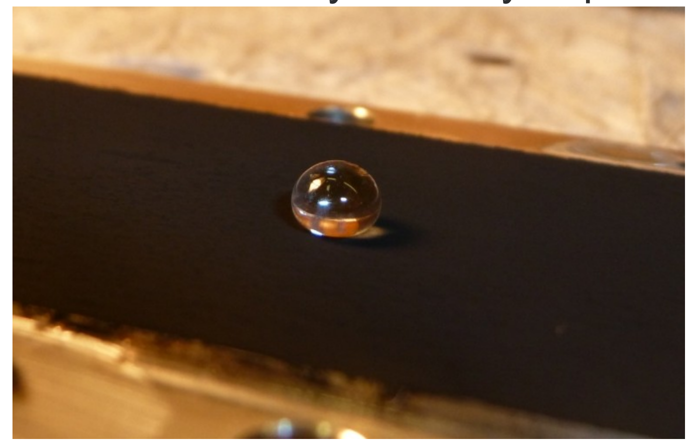
Inlet **Outlet**

Warey, A., Bika, A.S., Long, D., West, D., Balestrino, S., and Szymkowicz, P.G., "Influence of Water Vapor Condensation on Exhaust Gas Recirculation Cooler Fouling", ***International Journal of Heat and Mass Transfer***, 65: 807-816, 2013.

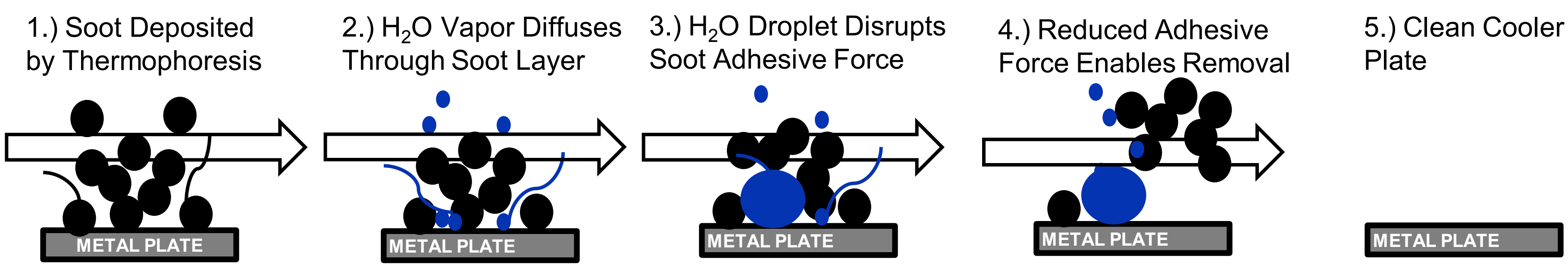
EFFECT OF WATER VAPOR CONDENSATION



Soot Particles/Layer are Hydrophobic



Removal Mechanism



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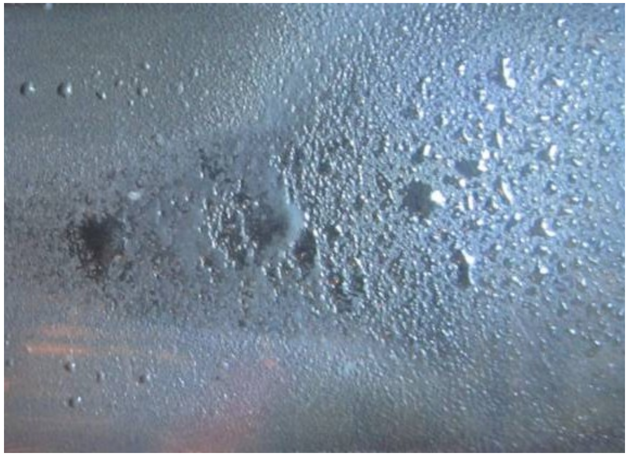
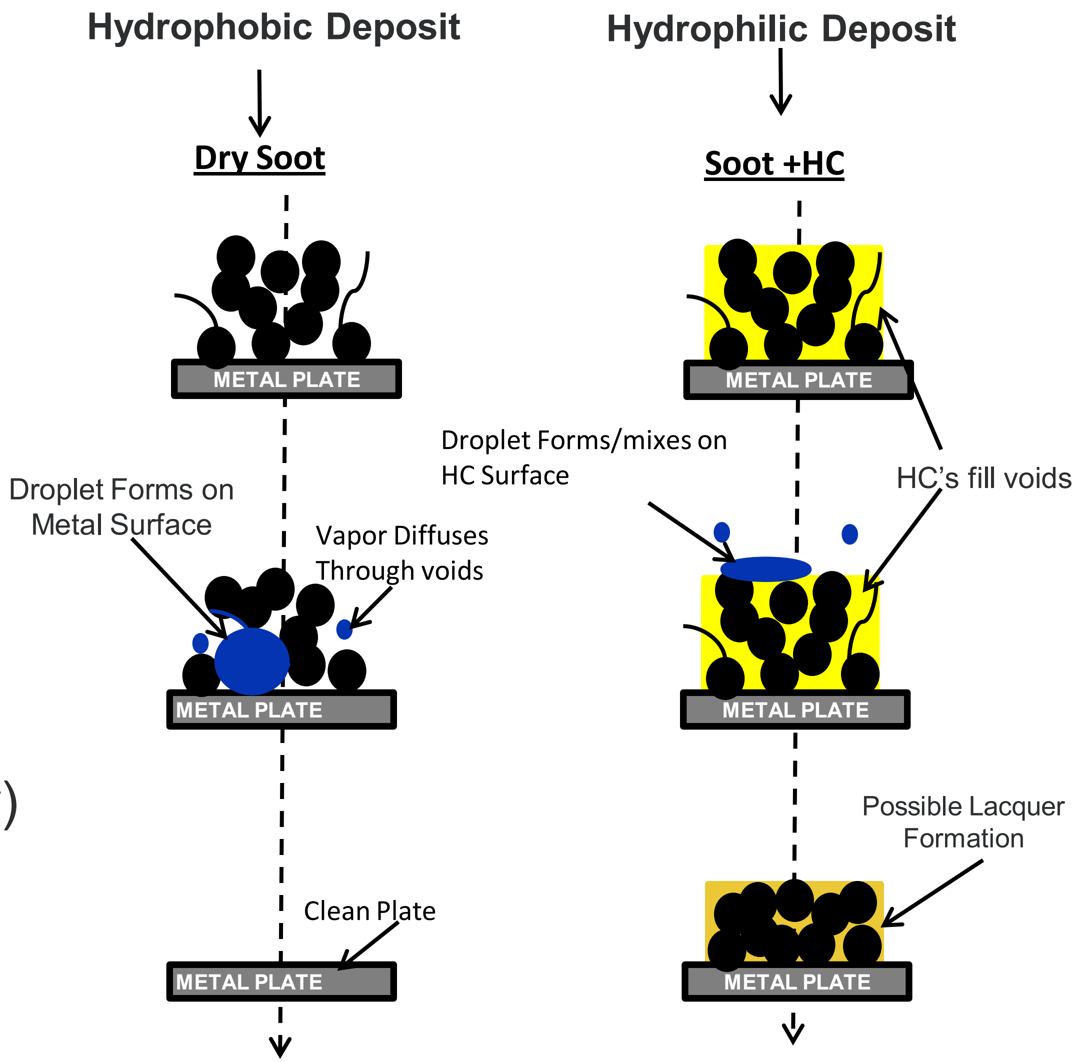
EFFECT OF WATER VAPOR CONDENSATION

Soot + HC yields Hydrophilic deposit



- Condensation of water vapor occurs on the surface of hydrophilic deposits (not below) and is unlikely to remove deposits.



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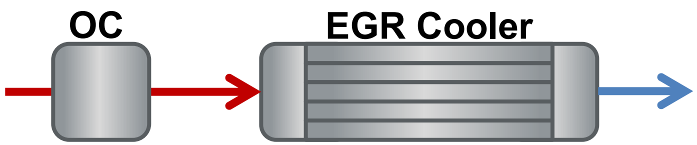
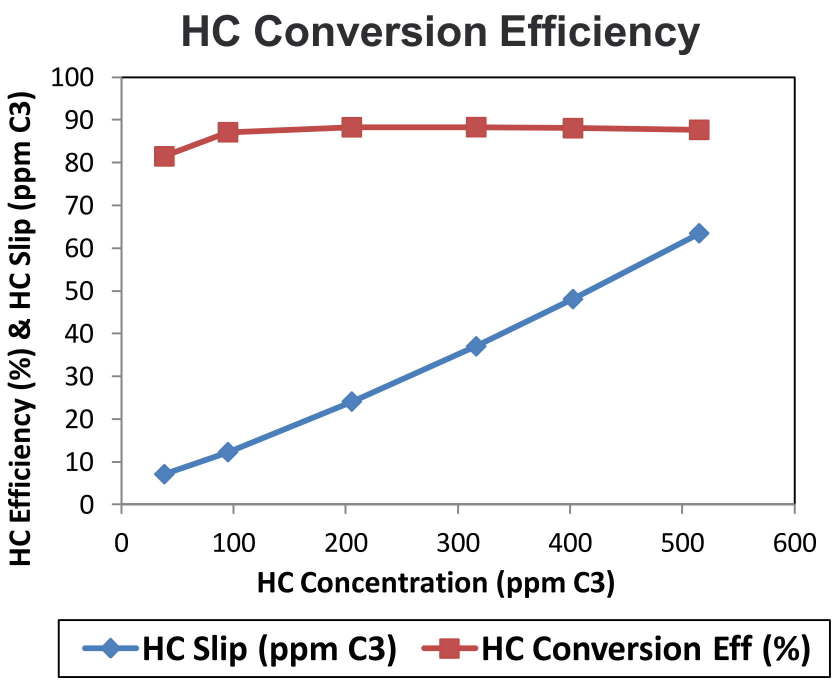
EFFECT OF OXIDATION CATALYST (OC)

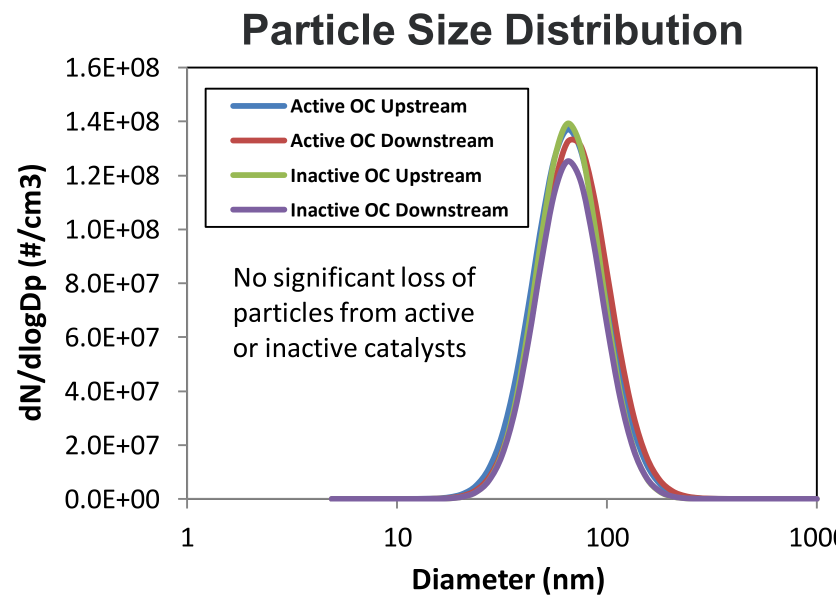


- Two Catalysts:
  - Active (Washcoat)
  - Inactive (NO Washcoat)

Specifications

Diameter	mm	45
Length	mm	120
Cell Density	cpsi	200 LS
Volume	L	0.19
Washcoat	g/ft^3	$67.5\ g/ft^3$ Pt / $22.5\ g/ft^3$ Pd





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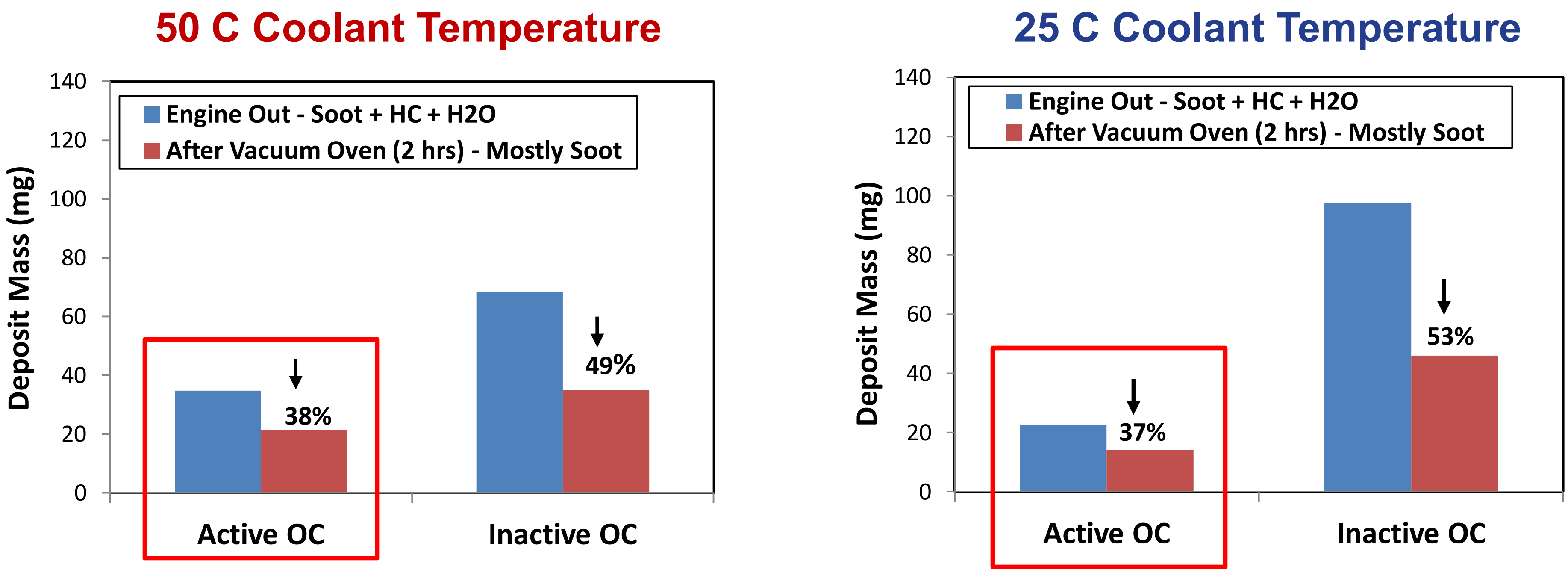
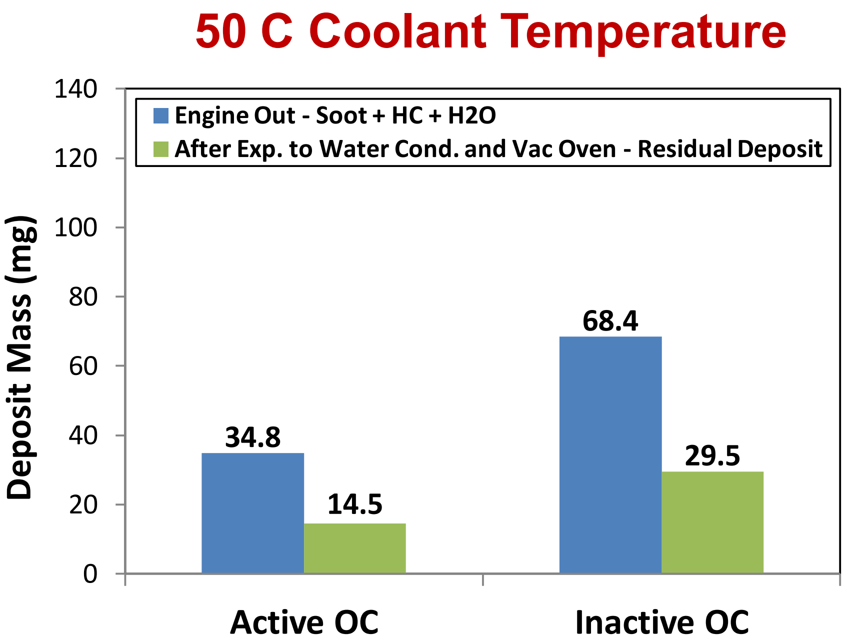
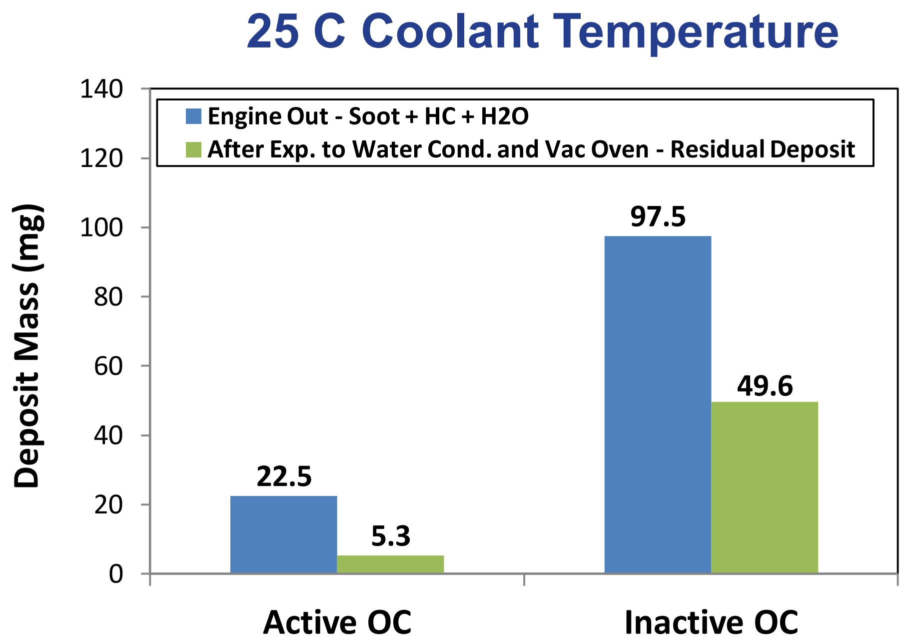


- An oxidation catalyst upstream of the EGR cooler results in lower accumulated deposit mass.

Warey, A., Bika, A.S., Vassallo, A., Balestrino, S., and Szymkowicz, P.G., "Combination of pre-EGR Cooler Oxidation Catalyst and Water Vapor Condensation to Mitigate Fouling", ***SAE International Journal of Engines***, 7(1): 2014.

EFFECT OF OXIDATION CATALYST (OC) + WATER VAPOR CONDENSATION





- Exposure to water vapor condensation in addition to the oxidation catalyst results in significant removal of deposit mass.

Warey, A., Bika, A.S., Vassallo, A., Balestrino, S., and Szymkowicz, P.G., "Combination of pre-EGR Cooler Oxidation Catalyst and Water Vapor Condensation to Mitigate Fouling", ***SAE International Journal of Engines***, 7(1): 2014.

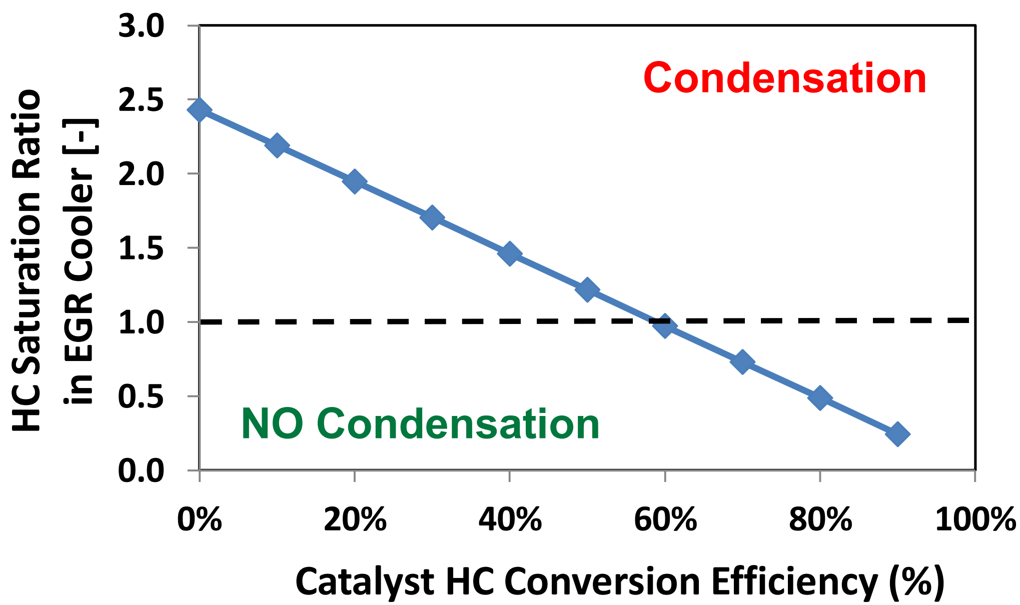
EFFECT OF OXIDATION CATALYST (OC)

- Saturation Ratio: $SR = \dfrac{P_v(T)}{P_{sat}(T)}$

$P_v\,(T)$: Partial pressure of the condensing species
$P_{sat}\,(T)$: Saturation pressure of the condensing species

- **Condensation typically occurs at SR > 1.0**

- **EGR Coolant Temperature: 50 C**
- **Engine-out THC: 250 ppm C3**
- **100% of the exhaust HC are assumed to be n-hexadecane ($C_{16}H_{34}$)**



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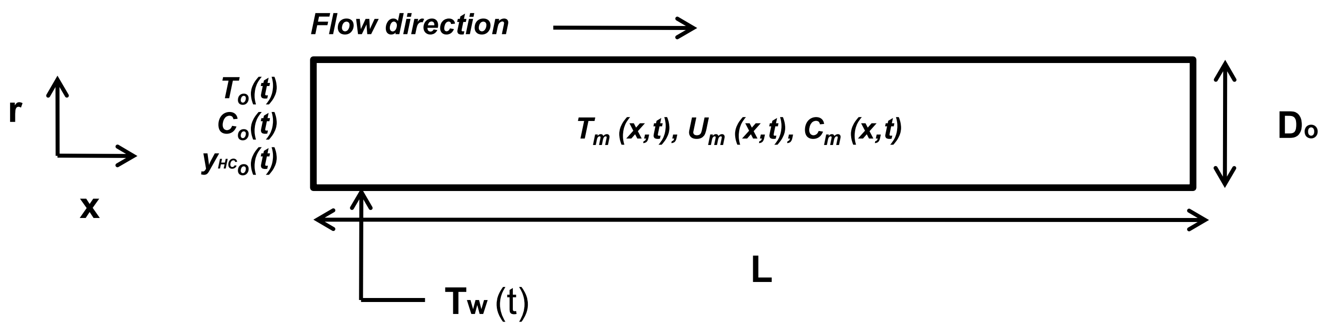
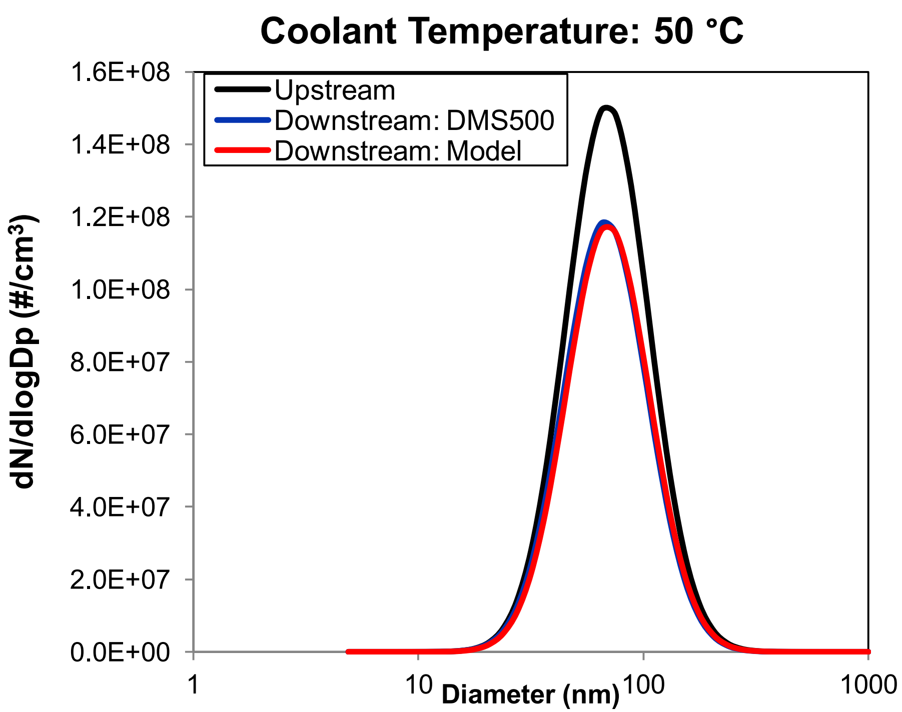
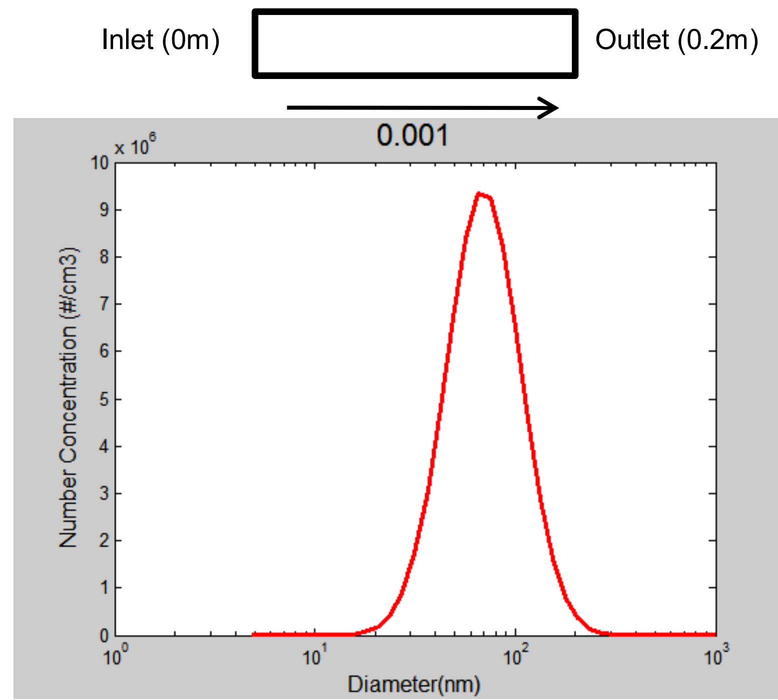
1D FOULING MODEL

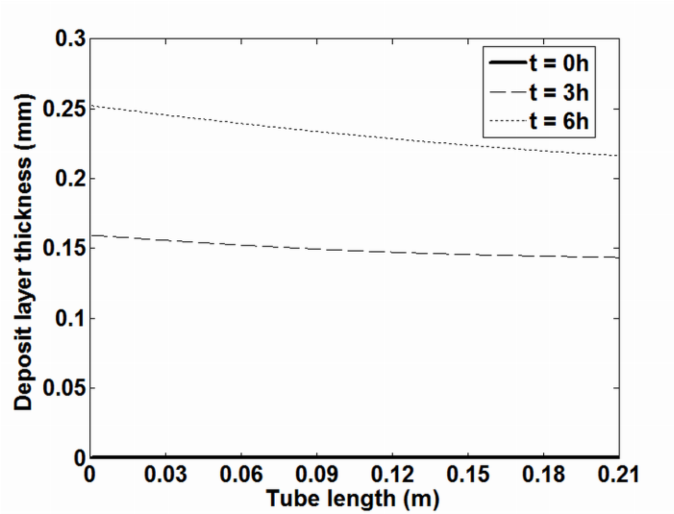


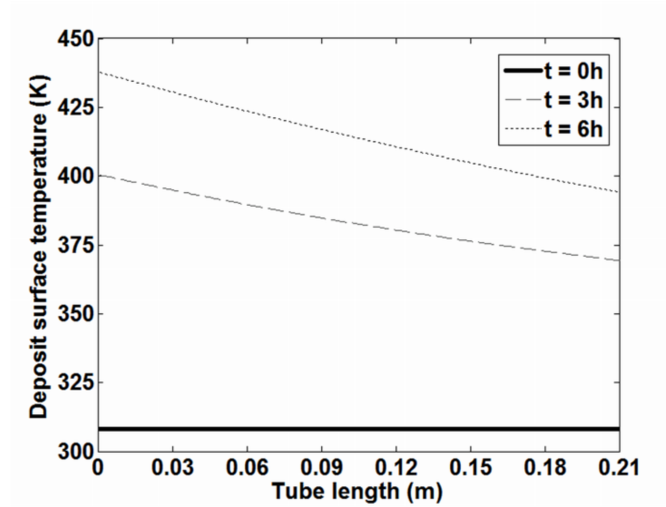


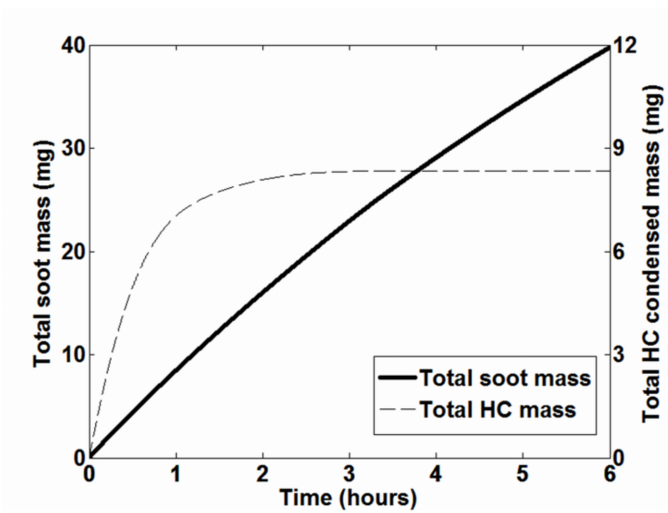


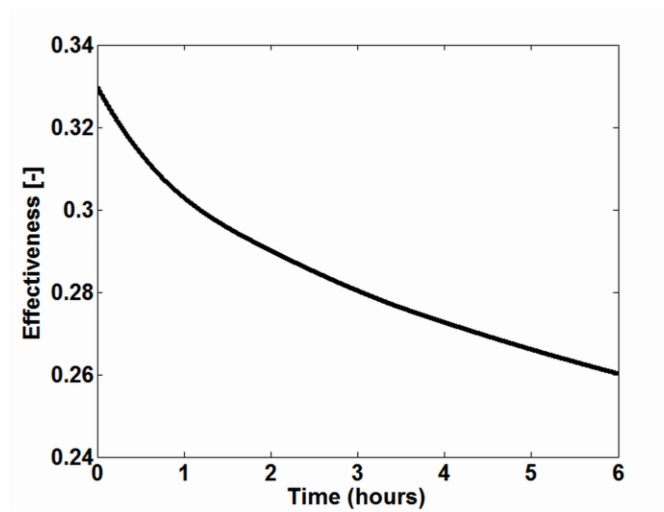
Warey, A., Balestrino, S., Szymkowicz, P.G., and Malayeri, M.R., "A One Dimensional Model for Particulate Deposition and Hydrocarbon Condensation in Exhaust Gas Recirculation Coolers", ***Aerosol Science and Technology***, 46 (2):198–213, 2012.

1D FOULING MODEL









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EGR COOLER FOULING SUMMARY

- Thermophoresis is the dominant mechanism for particle deposition in EGR coolers.
- Particulate fouling can be avoided if the gas velocity through the EGR cooler is above a critical flow velocity.
- Hydrocarbon condensation has the strongest influence on deposit morphology changing it from a dry porous layer to sludge or lacquer like deposit.
- Significant removal of accumulated deposit mass was observed by using an oxidation catalyst in combination with exposure to water vapor condensation.
- Based on the findings in this study on-board “cleaning” or regeneration of the EGR cooler by exposure to water vapor condensation does seem feasible.

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OTHER PROJECTS

- Fuel Effects on Low Temperature Premixed Compression Ignition (PCI) Combustion in a Light-Duty Diesel Engine

- Characterization of Particulate Matter (PM) Emissions from a 2007 Emissions Level Heavy-Duty Diesel Engine

- Development of an Electronic Sensor for Engine Exhaust Particulate Measurements – *Doctoral Dissertation*

- Effects of In−Cylinder Wall Wetting on Size and Mass of Particulate Matter Emissions in Direct Injection Spark Ignition Engines– *Masters Thesis*

- Guest Graduate – Argonne National Laboratory
  - Used laser scattering to measure the time resolved size distribution and mass of particulate matter (PM) emissions from a direct-injection gasoline engine

Thank You